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ACTIVATION OF AN ELECTRIC MOTOR WITH
CONTINUOUS ADJUSTMENT OF THE COMMUTATION ANGLE

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001]   This application is a U.S. national stage
application of International Application No. PCT/EP2004/051766
filed August 11, 2004, which designates the United States of
America, and claims priority to German application number
DE 103 52 749.4 filed November 12, 2003, the contents of which
are hereby incorporated by reference in their entirety.

TECHNICAL FIELD

[0002]   The invention relates to a method and to a device
for commutating the at least one phase of an electric motor.

BACKGROUND

[0003]   A converter (or commutator) is conventionally used
for polarity reversal of a phase of the electromagnetic
energizing field of an electric motor in the area of the zero
crossing point. The zero crossing point is taken to be the
position of the phase in which the phase is aligned in
parallel to the stator field of the motor, so that no torque
is exerted on the rotor of the motor.

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[0004]   With a modern electric motor, especially as used in drive systems of electric vehicles, commutation is mostly undertaken using power transistors.

[0005]   For the commutation of such an electronically commutatated motor a full electrical cycle, i.e. a full rotation of the energizing field by 360° is subdivided into similar shaped zones (or "states"). At the beginning of each zone the power transistors can be switched on or off for commutating a phase. The state of the phase is then retained until at least the end of the zone, but can optionally be overlaid by a pulse width modulated (PWM) signal.

[0006]   The division of the full cycle into zones defines a discrete number of possible commutation angles of the phase or of each phase. In this case that part of the full cycle during which the phase or each phase is activated, i.e. energized, is designated as the commutation angle. For a division of the full cycle into twelve equal zones, the commutation angle can for example be 180°, 150°, 120°,... . Previously an electric motor has frequently been operated with a fixed commutation angle.

SUMMARY

[0007]   The object of the invention is to specify a method for commutation of an electric motor through which a good drive result will be achieved for each operating point of the motor. A good drive result is expressed especially in a low and even current consumption of the motor at a comparatively

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high torque which remains stable over time, a low load on the
motor and/or on the converter, a good utilization of the power
of the motor, a good electromagnetic compatibility etc. The
object of the invention is furthermore to specify a
particularly suitable device for executing said method.

[0008]   In accordance with the invention there is provision
for continuously varying the commutation angle of the phase or
of each phase of the electric motor depending on the rotary
frequency of the energizing field and/or on an adjustable
variable characteristic for the drive power.

[0009]   The invention is based on the idea that varying the
commutation angle with the speed of the motor or the motor
power is advantageous. Thus operation of the motor at a
comparatively high commutation angle in the high speed or
power range leads to good utilization of the performance of
the motor, a low current ripple and a comparatively low power
dissipation. On the other hand, in the low speed or power
range the operation of the motor at a comparatively small
commutation angle has the advantage that the transistors and
capacitors of the converter are subject to a comparatively low
load, especially since in this way the use of PWM is not
necessary or is only necessary to a small degree. A further
idea underlying the invention is that a discrete, i.e. staged
change of the commutation angle would result in an
unsteadiness of the operating behavior of the motor. Such
unsteadiness could obviously be disadvantageous in the
operation of the motor. In particular the motor would be

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expected to jump backwards and forwards between two operating points in a transition area. This would cause heavy fluctuation to occur in power consumption and in torque, which would cause a comparatively high load to be imposed on the motor as a result of the constant speeding up and slowing down.

[0010]   The fact that the commutation angle in accordance with the invention is continuously varied enables the commutation of the motor to be adapted especially well to each operating point of the motor in a simple manner, without such an unsteadiness occurring.

[0011]   In an especially easy to implement embodiment of the invention the full cycle of the energizing field is subdivided into a number of zones, with the phase or each phase of the motor being commutatated accordingly depending on control patterns stored in these zones. In this case by varying the extent of the angle of at least two zones, the continuous variation of the commutation angle is made possible.

[0012]   Preferably these zones are subdivided into two groups with zones of the same group always featuring the same angular extent. In this case the zones of the different groups are arranged alternating to each other so that a zone of the first angular extent always follows a zone of the second angular extent and vice versa. During the course of setting the commutation angular the zones of the first group can in this case be shortened or lengthened in favor of the zones of the second group as regards their angular extent. The phase or

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each phase is usefully activated (or energized) via an odd number of consecutive zones. The commutation angle is consequently defined by the sum of the angular extents of 1,3,5, ... consecutive zones and thus varies with the ratio of the size of the zones of the two groups.

[0013]   Preferably the commutation angle is adjusted with regard to the power range of the motor such that the commutation angle for a low torque or for a low power of the motor is at its minimum and for a high torque or a high power is at its maximum.

[0014]   To adjust the commutation angle in line with requirements it is especially advantageous not just to include the pure rotary frequency as a control variable for the commutation angle but also an adjustable variable which, like the accelerator pedal setting of an automobile, is characteristic for the engine power. This adjustable variable is usefully derived from the (actual) rotary frequency and an associated required variable, especially using a PI (Proportional/Integral) regulator.

[0015]   The operating behavior of the motor is preferably further improved by pulse width modulation of the phase. This means that the phase or each phase within the commutation angle is not activated constantly but pulsed. The width i.e. the angular extent of this individual pulse is modulated, i.e. varied in its turn depending on the rotary frequency or the adjustable variable.

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[0016]   It has proved to be especially advantageous
preferably to employ individual parameters of those described
here for controlling the operating behavior of the electric
motor, i.e. the commutation angle and also the pulse width
modulation in a specific speed or power range of the motor. In
this sense pulse width modulation is used in the low-power
range of the motor while the commutation angle is kept
constant. In a high power range of the motor in this
embodiment of the inventive method the commutation angle is
then varied between its minimum value and its maximum value,
whereas the pulse width ratio is kept constant. The pulse
width ratio amounts here especially to 100%, i.e. the phase or
each phase is subject to constant activation during the
commutation angle.

[0017]   The method described here is optionally provided for
a unipolar activation as well as for a bipolar activation of
the phase or of each phase.

[0018]   A device features a converter which activates the at
least one phase of an electric motor. The converter for its
part is activated by a control unit, with this unit being
embodied to execute the method described here.

[0019]   The converter is preferably an electronic converter
equipped with power semiconductor components for switching the
phase or each phase. The control unit is in this case embodied
especially as a microcontroller equipped with the
corresponding software modules. Also conceivable would be an
application of the inventive method to a mechanical converter.

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The division into zones in accordance with the method could be
implemented here by a suitable, e.g. trapezoidal, design of
the current collector surfaces. A continuous change of the
commutation angle could in this case be achieved by a suitable
control unit through power-dependent axial displacement of the
converter in respect of the corresponding friction contacts.

[0020]   The control unit is preferably fed by a sensor with
the (time-dependent) orientation of the energizing field
and/or of its rotary frequency as an input variable.

BRIEF DESCRIPTION OF THE DRAWINGS

[0021]   Exemplary embodiments of the invention are explained
in more detail below on the basis of a drawing. The Figures
show:

    Figure 1 a schematic diagram of an electric motor with an
        upstream converter and a control unit for activating
        the converter,

    Figure 2 a schematic diagram of an orientation of the
        electromagnetic energizing field for a three-phase
        bipolar activated embodiment of the electric motor in
        accordance with Figure 1 within a full cycle,

    Figure 3 a schematic diagram of a control pattern for
        the electric motor in an embodiment in accordance with
        Figure 2

    Figure 4 in a diagram in accordance with Figure 3, a
        control pattern for a five-phase unipolar activated
        embodiment of the electric motor,

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Figure 5 a control element for deriving an adjustable
variable fed to the control unit as an input variable
on the basis of the (actual) speed and an associated
required variable,

Figure 6 in a schematic flowchart a method for
commutating the electric motor in accordance with
Figure 1 and

Figure 7 a diagram of the parameter settings depending
on the adjustable variable made in the course of the
method shown in Figure 6.

[0022]   Parts and variables which correspond to each other
are always shown by the same reference symbols in all the
Figures.

DETAILED DESCRIPTION

[0023]   The scheme outlined in simplified form in Figure 1
shows an electric motor 1 with a rotor 3 rotating within a
stator 2. The rotor 3 carries an energizer circuit 4 for
generation of an electromagnetic energizing field Fl, which
rotates with the rotor and thereby against a fixed
electromagnetic stator field H.

[0024]   As is not explicitly shown in the simplified scheme
in accordance with Figure 1, the electric motor 1 as a rule
features a number of energizing circuits 4. The energizing
circuit 4 thus produces only one component of the entire
energizing field F. An energizing circuit 4 as well as the

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components of the energizing field F generated by this circuit
are referred to jointly as phase Pi (i = 1,2, 3,...).

[0025]   The energizing circuit 4 of each phase Pi is
connected to a converter 5 by means of which a current flow
creating a field can be induced in the energizing circuit 4.
This is referred to as the activation or energizing of the
relevant phase Pi. In this case a distinction is made between
unipolar and bipolar activation. With unipolar activation the
current flow is binary, i.e. it can be switched on and off
between the "0" status and a "1" status. With bipolar
activation the current flow in the energizing circuit 4 can
have its polarity reversed so that the relevant phase Pi is
controllable between the status values -1, 0 and +1. With
polarity reversal of the current flow in the energizing
circuit 4 of the phase Pi the orientation of the associated
field components of the energizing field F is also inverted.

[0026]   The phases Pi are connected within the converter 5
by means of power transistors (not shown in greater detail).
The converter 5, and especially its power transistors, are
activated by a control unit 6 embodied as a microcontroller.
The control unit 6 is connected on the input side via a
control element 7 to a sensor 8 arranged in the electric motor
1, especially a Hall sensor.

[0027]   The sensor 8 picks up a measurement variable
characteristic for the time-dependent orientation of the
energizing field F and thereby of its rotary frequency f and
feeds this value to the control element 7. A required variable

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f0 for the rotary frequency is also fed to the control element 7. On the basis of the (actual) rotary frequency f and the associated required variable f0 the control element determines in a manner described in greater detail below an adjustable variable S and feeds this to the control unit 6.

[0028]   The converter 5 and the control unit 6 together with the control element 7 and the sensor 8 form a device 9 for commutating the phase or each phase P_i of the electric motor 1.

[0029]   The scheme depicted in Figure 2 shows an orientation, i.e. a "snapshot", of the energizing field F within a full cycle 10. A rotation of the energizing field F by a full circle of 360° is referred to as a full cycle. In the diagram shown in Figure 2 the electric motor 1 is embodied as a three-phase motor for bipolar activation. The energizing field F thus includes the three phases P1, P2 and P3. The direction of the arrow in this case indicates the polarity of the relevant field component. Thus the phase P1 is activated positively ("1" status), i.e. with connected to the positive supply voltage. The phase P3 is activated negatively ("-1"- status), i.e. connected to the negative supply voltage or GND. The phase P2 is not activated ("0" status), as is shown by the missing tip to the arrow.

[0030]   The full cycle 10 is subdivided into twelve zones Z_i (i = 1,2,...,12). The direction of the stator field H runs in the diagram through the zones Z6 and Z12. The division of the full cycle 10 into zones Z_i is used` for simplified activation

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of the current ender 5, in that the status of a phase Pi can
always be changed if the phase crosses the border line between
the two zones Zi. In accordance with Figure 2 each phase Pi is
activated positively on passing from zone Z0 to Z1 (0 -> 1)
and on passing from zone Z5 to zone Z6 is deactivated again (1
-> 0). On passing from zone Z6 to zone Z7 phase Pi is
activated negatively (0 -> -1) and on passing from zone Z11 to
Z12 is deactivated again (-1 -> 0).

[0031]   The angle between activation and deactivation of a
phase Pi is referred to as the commutation angle α. The zones
Zi enclosed within the commutation angle α together form a
commutation area 11. In the division of the full cycle 10 into
twelve equal zones Zi shown by way of an example in Figure 2,
each with an angular extent of 30°, and commutation areas 11,
the fifth zone Zi in each case amounts to the commutation
angle α = 150°.

[0032]   The angle between the orientation of the stator
field H (and thereby the zero crossing point of a phase Pi)
and the beginning of the commutation area 11 is designated as
the ignition angle ß. In the example shown in Figure 2 the
ignition angle ß is 15°.

[0033]   To enable the commutation angle α to be adjusted
continuously the angular extent of the zones Zi is variable.
The zones Zi are in this case divided up alternately into a
first group comprising the odd-number zones Z1 (1 =
1,3,5,...,11) and a second group comprising the even-number

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zones Zm (m = 2,4,6,...,12). The zones Z1 of the first group
in this case contain an angular extent of

$$\delta 1 = \frac{360°}{n} + \Delta\delta.$$ EQN 1

The zones Zm correspondingly receive an angular extent of

$$\delta 2 = \frac{360°}{n} + \Delta\delta.$$ EQN 2

In this case n identifies the total number of the zones Zi,
thus in the example shown in Figure 2 n = 12. The following
equation then applies for the difference angle $\Delta\delta$

$$-\frac{360°}{n} \leq \Delta\delta \leq \frac{360°}{n}.$$ EQN 3

[0034]   Figure 3 shows a schematic diagram of a control
pattern 12, as stored for the activation of the converter 5 in
the control unit 6. The control pattern 12 in accordance with
Figure 3 is designed for a three-phase, bipolar electric motor
1, corresponding to the scheme shown in Figure 2. The control
pattern 12 is presented in the form of a two-dimensional
diagram, on the horizontal axis 13 of which the orientation
angle γ of the phase P1 within the full cycle 10 (cf. Figure 2)
is plotted. The adjustable variable S is plotted continuously
along the vertical axis 14. The stored control pattern 12 is
also defined within a predetermined interval for each given
value of the adjustable variable S. To present the information
more clearly the control pattern 12 in Figure 3 is only shown

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for three typical selected discrete values S1, S2 and S3 of
the adjustable variable S.

[0035]   In the diagram of the control pattern 12 in
accordance with Figure 3 the zones Zi are expressed as
surfaces arranged next to one another in a horizontal
direction, delimited from each other by dashed lines. In
compliance with the orientation angle γ plotted on the
horizontal axis 13 the zone labeling shown in Figure 3 also
relates to the orientation of the phase P1 as reference phase.
To this end the position of the phase P2 is always offset by
four zones, the position of the phase P3 is always offset by
eight zones. The status of each phase Pi for a given value S1,
S2, S3 of the adjustable variable S is shown Figure 3 is in
the form of a stepped function with the values -1, 0, 1
depending on the angle of orientation γ.

[0036]   It can be seen from Figure 3 that, depending on the
adjustable variable S, the size ratio $\delta 1/\delta 2$ of adjacent zones
Zi and Z(i $\pm$ 1) is varied. So for S = S1 the difference angle
$\Delta\delta$ is negative, so that $\delta 1 < \delta 2$. Conversely for S = S3 the
difference angle Ad is positive, so that $\delta 1 > \delta 2$. For S = S2
the special case shown in Figure 2 is obtained in which the
difference angle $\Delta\delta$ disappears and accordingly all zones Zi
have the same angular extent $\delta 1 = \delta 2$. The instantaneous
orientation of the phases P1, P2 and P3 shown in Figure 2 is
indicated in Figure 3 by a perpendicular lines labeled II.

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[0037]   By comparing corresponding commutation ranges 11 for
different values S1, S2, S3 of the adjustable variable S it
becomes evident that the commutation angle α (corresponding to
the length of the commutation area 11) is continuously varied
as a result of the change to the difference angle Δδ. As can be
seen directly from the diagram shown in Figure 3, the
following now applies

$$\alpha = m \cdot \frac{360°}{n} + \Delta\delta, \qquad\qquad\qquad \text{EQN 4}$$

with m designating the number of zones Zi within a commutation
area 11. In general m is an odd number. In accordance with
Figure 3, m = 5.

[0038]   Figure 4 shows an alternatively embodied control
pattern 12' which is designed for activation of a five-phase,
unipolar activated version of the electric motor 1. The
control program 12 in accordance with Figure 4 thus comprises
status functions for five phases Pi (i = 1,2,...,5) which, in
accordance with the unipolar activation vary between the
discrete values 0 and 1. Furthermore the full cycle 10 is
subdivided here into twenty zones Zi (i = 1,2,3,...,20). The
control pattern 12' otherwise corresponds to the control
pattern 12 described in Figure 3.

[0039]   The function of the control element 7 is shown in
more detail in Figure 5. It can be seen from this diagram that
the rotary frequency f picked up by the sensor 8 and the
associated required variable f0 are fed to a difference module

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15. This outputs a difference frequency $\Delta\delta$ to a PI
(Proportional/Integral) controller 16. The PI controller 16
creates the adjustable variable S, which - like the
accelerator pedal in an automobile - is a measure of the
instantaneous power of the electric motor 1.

[0040]   Figure 6 shows the method performed by the control
element 7, the control unit 6 and the converter 5 for
commutating the electric motor 1 in a schematic simplified
flowchart. Thereafter the adjustable variable S is picked up
by a module 17 and fed to a selection module 19.

[0041]   The selection module 19 checks whether the
adjustable variable S corresponds to at least one
predetermined threshold value S` which delimits a high
performance area 21 (Figure 7) of the electric motor 1 from a
low performance area 22. If the condition $S \geq S'$ is fulfilled
the module 24 is activated. On the other hand, i.e. if the
electric motor 1 is in the low performance area 23, it
activates a module 25.

[0042]   In each of the modules 24 and 25 rules for deriving
a number of parameters are stored depending on the adjustable
variable S. These parameters included the so-called pulse
width ratio R, the difference angle $\Delta\delta$.

[0043]   The pulse width ratio R is needed within the context
of a pulse width modulation of a phase Pi during the
commutation area 11. In this case the phase Pi is activated in
a pulse-like manner during the commutation area 11. The pulse

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width ratio R specifies in this case what proportion of the overall commutation area 11 is taken in by the sum of the pulses. Thus for a pulse width ratio of R = 50% the phase Pi during the commutation area 11 is in total only 50% energized whereas the remaining 50% of the commutation area 11 is taken in by pauses between the pulses. With a pulse width ratio R = 100% on the offhand the pulses begin immediately after one another so that the phase Pi is constantly activated for the entire commutation area 11. The frequency of the PWM signal is significantly higher than the commutation frequency.

[0044]   As can be seen from Figure 7 the commutation of the electric motor 1 in the high performance area 21 is controlled by variation of the difference angle $\Delta\delta$, and thus according to EQN 4 by variation of the commutation angle α. In the low performance area 23 on the other hand pulse width modulation is used to control the commutation.

[0045]   In the high performance area 21 the parameters R and $\Delta\delta$ are determined in accordance with the equations stored in a module 24

$$R = 100\% \qquad \text{and} \qquad \text{EQN 5a}$$

$$\Delta\delta = \Delta\delta min + c \cdot (S - S') \qquad \text{EQN 5b}$$

Where $\Delta\delta min$ is a predetermined minimum value of the difference angle $\Delta\delta$ and c is a predetermined constant which is selected so that $\Delta\delta \leq \Delta\delta max$. In accordance with EQN 4, if there is a change in the difference angle $\Delta\delta$, the commutation angle α is varied

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between a minimum value set in the low performance area 23 and a maximum value set in the high-performance area 20.

[0046]   In the low performance area 23 the parameters R and $\Delta\delta$ are set in accordance with the equations stored in module 25

$$R = \frac{S}{S'} \cdot 100\%$$ and   EQN 6a

$$\Delta\delta = \Delta\delta min$$ EQN 6b.

[0047]   If for example for the three-phase electric motor 1 in accordance with Figure 2 and Figure 3 the commutation angle α is to be between 120° and 150°, depending on the adjustable variable S, $\Delta\delta min = -360°/n$ and $\Delta\delta max = 0$ are to be selected.

[0048]   The parameters R and $\Delta\delta$ are fed to an activation module 26 which activates the power transistors of the converter 5 on the basis of the control pattern 12,12'. Each switching process predetermined in the control pattern 12,12' with a corresponding orientation angle γ can be directly converted using the equation

$$t = t0 + \frac{\gamma}{360° \cdot f} + \Delta t$$ EQN 7

into a corresponding switching time. t0 in this case designates the time of the Lost 0 passage of the phase P1. The time t0 is supplied together with the current rotary frequency f by the sensor 8. The ignition angle ß can be set by using the predetermined time $\Delta\delta$.

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ABSTRACT

[0049]   In a method for improving commutation of the at
least one phase (Pi) of an electric motor (1), the commutation
angle (alpha) of the one or more phases (Pi) is continuously
varied in accordance with the rotary frequency (f) of the
electromagnetic energizing field (F) of the electric motor (1)
and/or in accordance with an adjustable variable (S) which is
characteristic of the driving power. A device (9) suitable for
carrying out the method has a frequency converter 5) and a
control unit (6) controlling the same and adapted to carry out
the method.